

Solar-Terrestrial Interactions

Stephen W. Kahler

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**AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Rd
AIR FORCE MATERIEL COMMAND
Hanscom AFB, MA 01731-3010**

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This technical report has been reviewed and is approved for publication.

/signed/
Robert A Morris, Chief
Battlespace Environment Division

/signed/
Stephen W. Kahler
Research Physicist

/signed/
Joel B. Mozer, Chief
Space Weather Center of Excellence

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13. SUPPLEMENTARY NOTES The work reported here covers only the last 11 years of task work originally begun in the 1970s under the leadership of Dr. Margaret Shea at AFRL.					
14. ABSTRACT This report covers a basic research (6.1 level) task on solar-terrestrial interactions carried out in the Space Weather Center of Excellence over an 11-year period for the Air Force Office of Scientific Research. This includes work on characterizing and predicting solar activity as characterized by sunspot numbers, the occurrence of solar coronal mass ejections (CMEs), energetic (1 MeV < E < 1 GeV) particle events, the solar wind, and geomagnetic storms. The investigators, working at Hanscom AFB, MA, have used many different kinds of space- and ground-based observations and have collaborated with workers at various institutions in this work. The task annual summaries are given and preceded by synopses of highlighted work for each year's report and followed by a complete listing of the publications funded by the task.					
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1. EXECUTIVE SUMMARY

The Solar-Terrestrial Interaction task carried out at Hanscom AFB by the solar section of the Air Force Research Laboratory (AFRL) Space Weather Center of Excellence and its predecessors is summarized for the years 1997-2007. The task began in the 1970s and was continued every year through FY2007, at which point it was terminated. The Air Force Office of Scientific Research (AFOSR) was the sole funding agency. Dr. M.A. Shea was the original task leader, and on her retirement from AFRL in 1997, Dr. S.W. Kahler continued in that role. The goals of the task were to understand energy transport in the interplanetary medium and to improve space weather prediction techniques.

The scope of the work includes solar transient phenomena and activity, the propagation of solar disturbances, such as coronal mass ejections (CMEs) and solar energetic particles (SEPs), through the interplanetary medium, the characteristics of the magnetic fields of the interplanetary medium, and the time variations and causes of geomagnetic disturbances. The scientific progress narratives from each year's annual task report are reproduced in detail. These are preceded by short summary discussions of selected topics from each of the annual reports to give a broad indication of the scope of the work. The conclusions section is a listing of the specific research topics from the most recent annual reports. The appendix contains all the reported publications, including titles, for the included years.

2. INTRODUCTION

The Solar-Terrestrial Interactions task was begun in the 1970s under the leadership of Dr. M.A. Shea. It was used to fund a large number of intra- and extra-mural research projects in the area of solar-terrestrial physics. The two task research objectives have always been broadly stated:

- Understand Energy Transport in the Interplanetary Medium
- Improve Space Weather Prediction Techniques

When Dr. Shea retired in 1997, Dr. S.W. Kahler became the task scientist and continued in that role through the end of the task on 30 September 2007. This final report begins with the last annual report under Dr. Shea and concludes with the FY2007 report, for a total of 11 years. Annual reports of earlier years are not easily available and no attempt is made to include that work here. The task was funded by the Air Force Office of Scientific Research at continually decreasing levels from well over \$1,000,000 per year in FY1987 to \$136,000 in FY2007. The AFOSR funding officers have been Dr Henry Radowski, Dr. Paul Bellaire, and Dr. David Byers.

A final report, which included all research presentations and publications funded under the task, was submitted to AFOSR for each year of the task. The essential research work accomplished for the year was summarized and followed by a forecast for expected work for the following year. Because the work has been so broad in scope and carried out over a long period by a number of individuals, the plan here is first to select and present just one highlight from each year to give the nonspecialist a flavor of the work and its significance. Beginning with Section 3.2 we then reproduce the research summaries for each year for the interested specialist. The appendix gives all the task publications by report year as an additional reference for the specialist. Within each year the refereed publications are given first and the unrefereed publications last. Titles are included to help guide the interested reader to the literature. As a rule, publications covering the work summarized in one year will be listed in the following year.

3. RESULTS – ANNUAL SCIENTIFIC SUMMARIES

3.1 Annual Summary of Selected Results

In FY1997 work was finished on the calculation of geomagnetic cutoffs on the world grid. These cutoffs determine the minimum energies of charged particles that can reach given locations in the magnetosphere as they are guided by the Earth's magnetic field. The cutoffs are needed to calculate radiation doses expected at satellites and spacecraft and become crucial during large solar energetic particle events.

In FY1998 a solar energetic ($E > 10$ MeV) particle (SEP) event was related to a quiescent filament eruption and interplanetary radio burst. SEP events have traditionally linked to the occurrences of large flares on the Sun, so finding a SEP event related to a filament eruption from outside any active region gives a better insight into the origins of SEP events. This finding is a key point in establishing that shocks driven by CMEs, rather than solar flares, are the important sources of the SEP events.

In FY1999 the role of halo coronal mass ejections (CMEs) observed on the SOHO spacecraft in producing solar wind disturbances and geomagnetic storms was clarified. The halo CMEs are generally the largest and most energetic of all CMEs, hence are warnings of potentially large

geomagnetic disturbances. However, not all halo CMEs will result in geomagnetic storms, so it is important to determine which of those CMEs are the most significant for geomagnetic storms. Characteristic signatures of dimming of coronal brightness in the EUV and X-ray range provide evidence of the spatial origins of CMEs, which is not always evident from the CME observations alone.

In FY2000 studies of the thin nitrate rich layers in polar ice cores revealed that these layers have a characteristic short time scale (< 6 weeks) and are highly correlated with periods of major solar-terrestrial disturbances. This opened up the ice core data as a valuable resource for understanding SEP events before the spacecraft era. A one to one correlation found between the seven largest solar proton fluence (intensity integrated over time) events observed since 1936 and corresponding nitrate events allowed a conversion factor to be established between the impulsive transient nitrate concentrations and the >30 MeV solar proton fluence. This then enabled the determination of proton fluences from the 70 largest impulsive nitrate events between 1561 and 1950. The interesting conclusion that several solar proton events having fluences an order of magnitude greater than measured during the satellite era have occurred in the past 400 years suggests that we have seen a relatively benign particle environment over the last 40 years.

In FY2001 a study of the limits to predicting the arrival times of interplanetary shocks at 1 AU showed a fundamental limit of about one day in the achievable accuracy of the predictions. The 1 AU arrival times of shocks, driven by CMEs, are needed as accurately as possible to know when geomagnetic storms may be expected. Long term predictions, greater than a few hours, of the arrival of interplanetary disturbances require not only observations of solar inputs but some understanding of the propagation of the disturbances through the interplanetary medium. Previous work had neglected interplanetary inhomogeneities such as high speed streams. A mathematical model containing descriptions of the shock waves and their interaction with interplanetary inhomogeneities was developed. The typical errors in estimates of transit times arising from uncertainties in the structure of the interplanetary medium are on the order of a day. This uncertainty is the cause of the fundamental limitation on how well one can predict the onset of geomagnetic disturbances at Earth, once the initial solar disturbance has been observed.

In FY2002 initial work found SEP events at 1 AU occurring in solar fast wind regions even though the higher solar wind flow speeds and Alfvén speeds should limit CME-driven shocks and the lack of suprathermal ion velocity tails should limit the availability of seed particles for acceleration to high energies. This work was extended in the following year and suggests that our understanding of the conditions required for SEP production at CME-driven shocks may be very incomplete.

In FY2003 the cause of the semi-annual variation of geomagnetic activity in 1954 and 1996, two years with pronounced six-month waves in geomagnetic activity, was determined. The variation of geomagnetic activity has long been known to peak during the equinoxes. Three theories have been proposed for the basic explanation, but only now have the diurnal temporal variations of these disturbances allowed us to separate out the causes. For both of these years, the semi-annual variation apparently resulted from equal contributions of the three principal mechanisms: axial, equinoctial, and Russell-McPherron. During 1954 and 1996, the axial and Russell-McPherron effects were enhanced by a favorable Rosenberg-Coleman polarity effect and a solar minimum solar magnetic field structure (low tilt angle). This is in contrast to the long run (decades to centuries) of geomagnetic activity where the six-month wave is primarily ($\sim 70\%$) due to the equinoctial hypothesis.

In FY2004 an analysis of the statistics of solar wind heat-flux electron pitch angles was carried out to look for three expected populations in the parallel to perpendicular ratios. The populations were expected based on the heat flux anisotropies as basic tools for determining polarities (sun-pointed or antisun-pointed) of interplanetary fields. The plots of the parallel-to-perpendicular electron ratios to the anti-parallel-to-perpendicular ratios show two population peaks corresponding to heat-fluxes directed parallel and anti-parallel to the interplanetary magnetic field. However, they do not show a distinct population that might be expected to represent the bidirectional flows associated with closed magnetic field topologies. The result calls into question the common technique of determining the magnetic field topologies based on the empirically determined bidirectional flows.

In FY2005 a geomagnetic index, the interdiurnal variability (IDV) was devised to use as a probe of interplanetary magnetic field strength at 1 AU. The index is essentially independent of solar wind speed and was used to determine the interplanetary field back to 1872. That determination showed a sharp difference from the results obtained by Lockwood and colleagues, which showed significant large increases in the interplanetary field over that time. The result provoked a critical reaction from Lockwood. The IDV was later used to infer that there is a minimum level of the interplanetary field of ~ 4.5 nT, which is usually reached during minimum and holds even during the grand minima of solar activity. A previously derived interhour variability (IHV) index had been used to show that the widely used geomagnetic aa index had been recalibrated at a point in the past. The aa index had been used to determine the history of the interplanetary magnetic field values at 1 AU back to about 1860.

In FY2006 electron-to-proton ratios examined for solar energetic particle SEP events observed during solar cycle 24 revealed two distinct classes of SEPs: (1) a group of events with weak proton intensities that have high electron to proton (e/p) ratios ranging from $\sim 10^2 - 2 \times 10^4$, and (2) a well-defined branch with strong proton intensities with e/p ratios ranging from $\sim 10^1 - 2 \times 10^2$. Events with strong abundance enhancements of trans-Fe elements form a prominent subset of “population 1” and are absent from “population 2”. Based on their high e/p ratios, trans-Fe enhancements, poor association with decametric-hectametric solar radio type II bursts, and inferred small interplanetary emission cones, population 1 SEP events are attributed to acceleration in solar flares. For population 2 events, the evidence indicates a dominant shock process as the origin. This work addresses one of the fundamental problems of SEP research – the number and characteristics of various SEP classes.

In FY2007 methods to correct the solar polar magnetic field measurements of solar synoptic maps and to improve the coupling between the inner and outer coronal field models were developed to improve the predicted solar wind parameters at 1 AU. Correcting the polar fields is most important during solar minimum when the fields are strong there and thus have greatest influence on the global magnetic field configuration. The potential field source surface model (PFSS) has served as the boundary between the lower coronal field and the outer fields extending into the solar wind. A more flexible coupling between the two models reduced the discontinuous behavior of the magnetic field across the model interface surface and substantially reduced the calculated current flow on this boundary surface.

3.2 Geomagnetic Cutoff Rigidities (FY 1997)

Calculations of geomagnetic cutoff rigidities utilizing the capabilities of the PL Maui High Performance Computer Center were completed. The effects of the decreasing geomagnetic field on radiation exposure to aircraft and satellites were also determined. A confirmation and new explanation for the 22-year cycle of geomagnetic activity was developed. The 22-year cycle in

geomagnetic activity, characterized by high activity during the second half of even-numbered solar cycles and the first half of odd-numbered cycles, had been explained by the Sun's polarity and the coupling of the solar wind to the magnetosphere. The new work points to the systematic difference between solar activity in odd and even numbered cycles and has implications for forecasting the peak sunspot number of the coming solar cycle. Thus it is important for the long-range space weather forecasts used to plan Air Force space missions.

3.3 Solar Energetic Particle Mechanism Studies (FY 1998)

A new prediction was made of the peak sunspot number (SSN) and the size distribution of geomagnetic storms for the (then) current solar cycle 23. Collaborative work was done to relate halo coronal mass ejections (CMEs) observed on the SOHO spacecraft to associated solar wind disturbances and geomagnetic storms. Work was begun on new algorithms to detect and analyze interplanetary shocks in the solar wind for use on L1 spacecraft data to improve predictions of geomagnetic disturbances that degrade USAF systems in space. Electron heat flux data from satellite instruments were used to determine the magnetic sector structure of the interplanetary magnetic field (IMF) and to study the propagation and structures of interplanetary CMEs within that structure. A solar energetic particle (SEP) event was related to a quiescent filament eruption and interplanetary radio burst, and a spectral invariance was found in gradual SEP events. The injection profiles of several particle ground level events were investigated. The origin of solar and interplanetary type II radio bursts was explored.

3.4 Coronal Mass Ejection Studies (FY 1999)

The solar wind electron heat fluxes were studied to determine that at least 2 and possibly 6 of 14 magnetic clouds do not fit the popular model of a single flux rope. In addition, the bidirectional electron heat fluxes in structures following some magnetic clouds indicate that they can not be trailing legs of flux ropes. A statistical analysis of interplanetary coronal mass ejections (ICMEs) in large magnetic sectors shows that their legs nearly always lie near the heliospheric current sheet, although the ICMEs themselves may be widely distributed within the magnetic sector structure. Deficiencies in a popular model of interplanetary shocks were explored and discussed in some detail. An attempt to find solar energetic particles (SEPs) associated with solar postflare magnetic loop systems showed that such structures are very unlikely sources of interplanetary SEPs. A limited comparison of fast CMEs and coronal structures did not show any characteristic signatures that could be associated with enhanced SEP production from a CME shock, although a preexisting SEP event made a large SEP event more likely. Analysis of energetic electron data showed that electrons also participate with the ions in exhibiting invariant spectra near the time of shock passage at the observer.

We studied halo CMEs observed by SOHO to: 1) investigate their utility for space weather forecasting, 2) improve our understanding of the internal structure of CMEs, and 3) test software applications detecting and imaging CMEs with the future SMEI experiment. We found that during a 6-month period in 1997, all halo CMEs associated with near-Sun center surface activity had shock and magnetic cloud signatures at 1AU and produced moderate storms at Earth. Studies of SOHO CMEs showed evidence of magnetic disconnection of field lines near the Sun. Flux rope-type structures appear to be a separate class of CMEs which erupt fully formed from near the solar surface. Coronal dimmings in the extreme ultraviolet images were identified as a "footprint" of CMEs. In larger events during the rise of the solar cycle the dimmings were found to extend well away from the associated active region and flare and often reached across the solar

equator. Such extensive dimmings underscore the complexity of CME fields at solar maximum, apparently involving interconnections of multiple active regions.

We re-examined the cause of the semiannual variation of geomagnetic activity. This variation is marked for strong storms (e.g., no great ($A_p > 100$) storms in December since 1932!) and thus understanding its cause has clear implications for space weather forecasting. It was found that the seasonal variability of southward field (in the GSM coordinate system), commonly presumed to be the cause of the semiannual modulation of geomagnetic activity, was too small to account for the effect. Instead evidence was presented that the key controlling parameter is the acute angle between the solar wind flow direction and Earth's dipole axis. The coupling efficiency of the magnetosphere is maximized when this angle is closest to 90 degrees. Evidence was also presented for a seasonal dynamic of the ring current that yields a modulation of the Dst index independent of a change in ring current intensity. Parts of this work on the semiannual variation – which represents a significant departure from the current view – have already received independent confirmation. These new findings can be used in algorithms that translate upstream solar wind parameters measured by ACE, for example, into predicted geomagnetic indices.

3.5 Coronal Mass Ejection Relation to Solar Energetic Particle Events (FY 2000)

Several collaborative studies of interplanetary coronal mass ejections (ICMEs) were carried out using the tool of solar-wind electron heat fluxes to determine the topology and polarity of interplanetary magnetic fields. The first study compared magnetic clouds, a signature of ICMEs, with their bidirectional heat fluxes to determine how much of the magnetic clouds appeared to have closed magnetic field topologies. The range of bidirectionality in the clouds was essentially from 0 to 100%, and there was less counterstreaming in the clouds observed near solar minimum than near maximum. The larger magnetic clouds were statistically more closed than smaller clouds, consistent with a model in which the clouds gradually become magnetically open to the interplanetary medium. A second study, of extreme density variations in the solar wind, showed that while ICMEs have average densities comparable to the slow solar wind, the lowest observed densities of $n < 1$ p/cc are often seen in high magnetic pressure regions of ICMEs. In the third study the heliospheric current sheet structures were studied during the time of an alignment of the Ulysses spacecraft at 5 AU and the Wind spacecraft at 1 AU. A large-scale coherence was found between the two spacecraft, but on a size scale of a few degrees a high variability was found, with transient features such as ICMEs playing an important role. All these studies of the interplanetary magnetic field structure are directed toward understanding and predicting the behavior of ICMEs, which cause the large variations in space weather.

Another collaborative study has involved the comparison of solar energetic ($E > 1$ MeV) particle (SEP) events observed by the Wind spacecraft with the associated CMEs observed by the SOHO spacecraft. There are now over 50 such events that can serve as the basis of statistical studies. The associated CMEs are found to be fast, as expected, but also much wider than average and to lie in and interact with the streamer belt. In separate studies the statistics of CME speeds and associated SEP intensities were related to each other and the statistics of SEP peak intensities and fluences were compiled. A possible role for ambient SEPs as the source population of CME shocks was also found using a database of SEP events from the GOES spacecraft. The variation and solar longitudinal behavior of the SEP spectral indices was also a part of the study. Another new project has been to validate the SEPTR program, which predicts the geographic locations of solar energetic particle cutoffs. This work has used data from the Proton Electron Telescope on the SAMPEX satellite. The goal is to test the SEPTR program under a variety of geomagnetic conditions and for at least several particle energies of SEP events. All this work with SEPs has

been directed toward an understanding of the origin and effects of SEP events, which constitute an important component of space weather.

The relationship between coronal shocks as revealed by metric type II bursts and coronal mass ejections was investigated. Coronal shocks are important for space weather as possible progenitors of the interplanetary shocks that signal the onset of geomagnetic storms and as accelerators of solar energetic particles (SEPs). Their role in both of these key areas is not as yet understood. It was found that while CMEs invariably accompany metric shocks, they may not always drive them. In at least some cases it appears that the coronal shocks are driven by ejecta internal to the CME. CMEs appear to be a necessary condition for such ejecta to occur, likely by opening field lines.

A collaborative effort with Goddard scientists investigated the solar wind sources of geomagnetic activity over the solar cycle. This study was made possible by work during the last decade that identified signatures of coronal mass ejections in the interplanetary medium. It was found that CME-related structures (shocks/post-shock flows/ejecta) account for about 50% of average geomagnetic index values at solar maximum and only about 10% outside of maximum. Corotating high-speed streams contribute 70% of average index values outside of solar maximum and 30% at maximum. The contribution from slow solar wind is constant at approximately 20% over the solar cycle. The Gnevyshev Gap, a long-standing puzzle in solar physics, was also investigated. The Gnevyshev Gap refers to a characteristic decrease in major solar events and associated geomagnetic activity at the peak of the sunspot cycle. It was found that solar wind speed and magnetic field decreased during the Gap in all components of the solar wind (CMEs, high-speed streams, slow solar wind). Thus the Gnevyshev Gap is a global solar phenomenon, apparently related to an observed depression in the open magnetic flux at the time of solar magnetic field reversal. This finding has implications for intermediate-term (few years) predictions of geomagnetic activity.

In a study of the semiannual modulation of the ring current geomagnetic index Dst, it was demonstrated that the Malin-Isikara effect, previously ignored in studies of the six-month wave in average Dst values, is likely the dominant contributor to this variation. Unlike the classical modulation mechanisms (axial, equinoctial, Russell-McPherron) that work by varying the energy input to the magnetosphere and therefore the intensity of the ring current over the course of the year, the Malin-Isikara effect is based on the seasonal deformation of the magnetosphere caused by the varying angle between solar wind flow and Earth's dipole axis. The magnetosphere is pushed southward in northern hemisphere summer and northward six-months later. This effective motion of the ring (and tail) currents relative to the magnetometer stations that make up the Dst network will result in a semiannual variation. It was determined that 50-70% of the amplitude of the six-month wave in average Dst values is caused by the Malin-Isikara effect, in comparison with 20-40% for the equinoctial effect, and 10% for the combined axial/Russell-McPherron mechanism. The Malin-Isikara effect represents a new probe of magnetospheric dynamics.

A crucial aspect of space weather forecasting is the accurate prediction of onset of geomagnetic activity based on detection and analysis of interplanetary shock waves by spacecraft located near the L1 Lagrangian point. Such measurements allow up to about an hour lead time in forecasting and in principle can serve as input to computer codes that simulate and forecast the behavior of the Earth's magnetosphere, ionosphere, and thermosphere. In order to do this, reliable measurements from one spacecraft of the shock normal direction and shock speed are required so that the transit time from the detection point to Earth can be computed. We have developed, for the first time, a complete analysis that solves the MHD shock jump conditions and fits an ideal

shock to data; the fitting procedure provides estimates (i.e., measurements) of the normal and speed. The new analysis extends and replaces existing work (i.e., Lepping and Argentiero, 1972; Vinas and Scudder, 1984). The new procedure will serve as the basis of software for operational use at AF 55SWXS.

Long term prediction, greater than a few hours, of the arrival of interplanetary disturbances requires not only observations of solar inputs but some understanding of the propagation of the disturbances through the interplanetary medium. A common approach to such predictions is to assume that the initial disturbances propagate through a highly simplified, e.g. spherically or axially symmetric, interplanetary medium, and that it is reasonable to neglect interplanetary inhomogeneities such as high speed streams. We have studied the effects of high speed streams and turbulence on the transit times of interplanetary shocks from the sun to Earth. A linear mathematical model that contains descriptions of the shock waves and their interaction with interplanetary inhomogeneities was developed. Using solar wind data for one solar cycle, we have shown that typical errors in estimates of transit times arising from uncertainties in the structure of the interplanetary medium are on the order of a day. This is a rather large error and should be taken into account in any future efforts to develop a long-term forecast capability.

A study of the thin nitrate rich layers in polar ice cores revealed that these layers have a characteristic short time scale (< 6 weeks) and are highly correlated with periods of major solar-terrestrial disturbances. A one to one correlation was found between the seven largest solar proton fluence events that have been observed since continuous recording of the cosmic radiation started in 1936, and the corresponding thin nitrate layers for the event date. A conversion factor was established between the impulsive transient nitrate concentrations and the >30 MeV solar proton fluence. This enabled the determination of proton fluences from the 70 largest impulsive nitrate events between 1561 and 1950. It was concluded that the impulsive nitrate events are reliable indicators of the occurrence of large fluence solar proton events, and that they provide a quantitative measure of these events. One of the interesting conclusions from this study is that several solar proton events having fluences an order of magnitude greater than measured during the satellite era have occurred in the past 400 years.

In a continuation of the above study, we have found a well-defined Gleissberg periodicity in large fluence solar proton events, with six well-defined solar minima, two in close association with the Maunder and Dalton minima in solar sunspot number. The present Gleissberg cycle was found to be one of the least effective in the production of large fluence solar proton events at Earth. The largest solar proton event identified was in 1859 and had an estimated > 30 MeV fluence of $18\text{-}36 \times 10^9/\text{cm}^2$. The high upper limit for fluence together with a predicted increase in solar proton event frequency have significant implications for space flight and space engineering. By using this technique with other ice cores, we have the potential to permit solar, geophysical, and other terrestrial investigations for more than 200,000 years into the past. These types of studies should help resolve the question of “how large an event” can be expected over specific periods of time.

3.6 Geomagnetic Storm Studies (FY 2001)

A computer model, SEPTR (solar energetic particle tracer), was developed to calculate upper rigidity cutoffs of energetic particles entering the magnetosphere. This model may serve as a tool for making space environmental predictions during solar energetic particle (SEP) events. We tested the model with SEP data from the 20 - 29 and 29 - 64 MeV proton channels of the Proton/Electron Telescope (PET) on the SAMPEX satellite for polar cap passes during large SEP events to determine the experimental geographic cutoff latitudes for the two energy ranges.

These latitudes were compared with the calculated cutoff latitudes based on the SEPTR program. Using the 1995 International Geomagnetic Reference Field (IGRF) model in SEPTR, the predicted cutoff latitudes were systematically too far poleward by about 4° to 10° for both energy ranges. Use of the Tsyganenko magnetospheric field model reduced the error to about 2° to 3° . In the latter case the latitudinal cutoff differences with increasing K_p is small.

An impulsive solar energetic particle (SEP) event observed on the Wind spacecraft on 1 May 2000 was associated with an impulsive solar active region M1 X-ray flare. The timing and position of a fast ($v = 960$ km/s), narrow CME observed in the Lasco coronagraph on SOHO made clear the connection between the CME and the flare and SEP event. Impulsive SEP events have long been associated with impulsive flares, but only gradual SEP events have thus far been found to be associated with CMEs. This is the first clear case of an impulsive SEP event with an associated CME.

Solar transient coronal holes (TCHs) are short-lived regions of dimmed X-ray intensity sometimes observed in association with coronal mass ejections and have been suggested as the magnetically open footpoints of associated transient flux ropes observed at 1~AU. We have used images from the Yohkoh Soft X-ray Telescope (SXT) to study the development of TCH events obtained in a survey of Yohkoh observations. We found that the boundaries closer to the magnetic neutral line generally move away from it as the closed-loop X-ray arcades expand. In addition, previously closed coronal loops at the ends of the arcades often continue to expand and open on the outer boundaries of the TCHs. The TCHs tend to disappear only by a net contraction of the boundaries, rather than by brightening within their boundaries. The location of a TCH appears to coincide with a large-scale curvature of the magnetic neutral line or the occurrence of a nearby active region at one end of the coronal eruption. The moving magnetic boundaries, uniformly dark interiors, and short lifetimes of TCHs pose significant problems for the interpretation that TCHs are footpoints of interplanetary magnetic flux ropes.

Coronal hole (CH) boundaries separate large-scale closed and open solar coronal magnetic fields and play a significant role in defining the slow solar wind. We used soft X-ray images from the Yohkoh Soft X-ray Telescope (SXT) to investigate the structure and changes of the boundaries of long-lived (several rotations) CHs which extend from the solar polar regions to midlatitudes. Such extensions appear to move across the photospheric structure, tending to rotate rigidly rather than differentially. To maintain the rigid form of the CH, magnetic reconnection must continually occur at each of its boundaries. We distinguish three kinds of CH boundaries in the SXT observations. The longest are those in large-scale magnetic field regions, which are generally ragged and not sharply defined. Changes at those CH boundaries appear to proceed gradually, with clear loop brightenings or dimmings only occasionally observed. Neither large-scale transient X-ray events nor coronal bright points appeared significant factors in long-term CH boundary development. The long loop lengths at the CH boundaries, their gradual motions and brightness changes, and the observation of smooth, straight long-lived boundaries at high latitudes suggested that reconnection of boundary field lines occurs in the high corona. The cases for reconnection at CH boundaries between open field lines only and between open and closed fields were considered to explain the observations.

Studies of the structure of the interplanetary medium continued. A study of four current sheet passages at both Wind and Ulysses when the two spacecraft were nearly aligned radially showed that the heliospheric current sheet is coherent as a global structure but highly variable in local structure over angular distances of a few degrees. A simple model was also proposed to explain how the total interplanetary magnetic flux remains constant while large injections of flux occur with coronal mass ejections (CMEs). The basic idea is that magnetic reconnection occurs

between a large closed CME loop and an adjacent open field line that produces a large single kinked open field line and a small closed loop in the solar corona.

An initiative on extreme space weather events was initiated to focus on “worst case” solar-terrestrial events including: large SEP events, great geomagnetic storms, low-latitude auroras, and transient radiation belts. Earlier work under this AFOSR task that identified the ψ -angle between the solar wind flow direction and Earth’s magnetic dipole was used to address the cause of the marked seasonal variation of the largest geomagnetic storms, with two-to-three times as many such storms occurring at the equinoxes than at the solstices. It was found that normalizing for the ψ -angle variation removed ~60% of this discrepancy, with the remainder attributed to the axial and Russell-McPherron hypotheses. Including the ψ -angle dependence in relationships between solar wind parameters and geomagnetic indices will allow a significant improvement in the prediction of great storms using upstream solar wind data from L1 or Sentry orbit. An analysis of the aurora of 14-15 May 1921 indicated that the lowest latitude of overhead aurora was ~40°, consistent with reports for the monster storm of 1859. Preliminary data and theoretical analyses were completed for “rogue” SEP events, large events whose > 10 MeV fluence can make up an appreciable fraction (up to half) of the cycle averaged fluence. It was found that converging shocks/CMEs were the most prevalent condition for the observation of a rogue event. Modeling showed that the preceding slower CME serves primarily to trap the particles; acceleration of particles as they bounce from shock to shock is relatively unimportant for producing the high peak fluxes observed between the barriers.

A 22-year pattern in the relationship between sunspot number and cosmic ray intensity was discovered: The 11-year cosmic-ray cycle appears to lag the sunspot cycle by ~1 year for odd-numbered solar cycles such as 19 and 21 while during even-numbered cycles such as 20 and 22, the sunspot number and cosmic ray intensity curves are essentially in phase. This finding was reported in the popular press and in a USA Today article. Randy Jokipii from the University of Arizona, a leading modulation expert, described it as “the last nail in the coffin” for the drift theory of modulation. A second published study on modulation presented evidence for the critical role of CMEs in blocking entry of cosmic rays to the heliosphere. It was pointed out that the CME rate closely tracks the sunspot number (anti-correlated with cosmic ray intensity) and that CMEs account for a significant fraction of the new magnetic flux injected into the heliosphere at solar maximum.

Two review articles on CMEs have been accepted for publication. The first of these, for the Journal of Geophysical Research, focused on the non-coronagraph manifestations of CMEs, including, global brightenings, coronal dimmings, waves (including Moreton waves and Type II radio bursts), and arcades visible in H-alpha, soft X-rays, and radio emission. It was pointed out that the standard sigmoid - flux rope eruption - twin dimming – arcade model of CMEs accounts for only a small fraction of all events. The second review, based on the S-RAMP Symposium in Japan in October 2000, was a free-ranging discussion of the origins of CMEs including recent observational and theoretical developments. It was conducted on a no-holds-barred world wide web site and included contributions from approximately 25 of the leading experts in this field. The premise behind this novel approach was to get scientists to speculate freely, since a new idea, even if wrong, may trigger a fruitful response in the mind of a colleague.

A workshop on SEPs was organized in conjunction with the 27th International Cosmic Ray Conference. Approximately 60 of the leading experts in this area convened for three days in Lüneburg Germany to discuss the relative importance of flares and shocks for SEPs. Recent evidence indicates that flares may play a more important role in large SEP events than is currently thought to be the case. A summary of the meeting was submitted to Eos.

A continuing study of solar proton events for the 23rd solar cycle indicates that the number of events in this solar cycle is expected to be similar to the total number of events for each of the previous four solar cycles. While the distribution of the events over the first five years of the 23rd cycle is different from the previous four cycles, it is most similar to the 20th solar cycle when major activity occurred during the declining years of the cycle.

Vertical cutoff rigidities for cosmic ray stations for 9 Epochs of the geomagnetic field were calculated. This set of cutoff rigidity values were determined at five-year intervals using the trajectory-tracing method through a quiescent geomagnetic field representation as described by the Definitive Geomagnetic Reference Field Coefficients for 1955-1990 and the International Geomagnetic Reference Field Coefficients for 1995. These values supersede all previously published values as the DGRF coefficients are the IAGA internationally accepted geomagnetic field models.

Simulations of the solar proton dose observed during the STS-28 flight in August 1989 have been continued. Considerable improvement has been realized by using a finer grid interpolation for the STS-28 flight ephemeris.

Prediction of coronal mass ejections and solar flares requires, in addition to accurate observations, a comprehensive theory of magnetized plasma in the solar atmosphere. The important physical properties that presumably determine the structure and stability of coronal structures are gravity, pressure, and force-free currents. Understanding the origins of the disturbances requires a theory that can treat all three simultaneously; we have developed for the first time a theory that does so. The theory is expressed in the form of a Poisson equation with a source term that describes the plasma and gravitational field properties, field-aligned current distribution, and magnetic field geometry. The formulation can match any observed photospheric magnetic field distribution and account for arbitrary pressure and temperature distributions in the corona. It is readily solvable by standard numerical methods. Such work has been attempted before, notably by B. C. Low in a series of papers in *Astrophysical Journal*; the present results carry Low's work to its logical conclusion, accounting for the important physical processes in a completely general way. Work in FY01 centered on the development of the theory of static plasma. .

3.7 Theoretical Developments Related to Interplanetary Phenomena (FY 2002)

It was shown that the reported doubling of the solar coronal magnetic field during the 20th century occurred primarily between 1900 and 1950. Since then, various indicators of the coronal magnetic field including cosmic ray intensity and the geomagnetic aa index have no clear trend.

From an investigation of coronal shocks and solar energetic particle (SEP) events it was found that: (1) < 50% of metric type II bursts are associated with SEP events; (2) when the metric type II bursts have a decametric/hectometric counterpart as observed by the WAVES instrument on the Wind spacecraft, the association rate with SEPs increases to ~ 85%. This suggests that shock acceleration of SEPs becomes more efficient above about 2 Ro (the nominal crossover between the metric and decametric range) or that shocks which survive to such heights are more likely to intercept open field lines connecting to Earth.

An analysis of shock-fitting algorithms was completed. This included the development of (1) local minimization criteria, (2) optimal global solution criteria, and (3) error estimates for the problem of fitting MHD shock model to data.

The theory of quasistatic structures in the solar atmosphere was extended to include photospheric convection. Work continued on numerical solutions of quasi-static coronal structures (looking for pre-conditions for CMEs).

A new theory of large-scale instability in collisionless plasma was developed in an effort to explain the origin of magnetospheric substorms. So far, the application to substorms has not been successful because conditions are required that are not observed.

We worked out a polar theory that incorporates molecular ions and shows that they are expected to be associated with large outflow speeds because of the change in the mean molecular degrees of freedom of the plasma.

We calculated vertical cutoff rigidities for spacecraft altitudes and developed an interpolation procedure for other locations that will become part of the AFGL Geospace Programs.

It was determined that the solar proton events for the 23rd solar cycle had a different distribution throughout the first six years of the cycle than the distribution for the previous four cycles. The number of solar proton events appears to be consistent with a six-year profile; the distribution is different.

The decay time scales of solar energetic particle events were studied to look for variations among the events and to relate them to the characteristics of the interplanetary medium. It was found that the decay times can vary by an order of magnitude and that for certain long-lived periods the decay times remain constant for all events during that period.

Narrow Coronal Holes (NCHs) are channels of open magnetic fields in the solar corona that may be a source of slow solar wind. The NCHs were identified in Yohkoh solar soft X-ray images and compared with the calculated source and properties of some slow solar wind flows. Contrary to the usual understanding, the NCHs appear to be a source of typical slow solar wind rather than the fast wind which is attributed to CHs in general.

The relationship between CMEs and near-solar dust has been investigated. It was found that CMEs contribute to decreasing the drift-in times of 3 to 30 micron dust grains with a small (~15%) solar cycle effect, in which the drift-in times decrease during solar maximum due to increased ion drag forces from CMEs.

An investigation of the magnetic field polarities at solar minimum using heat-flux electrons as a probe of the polarities has shown the polarity structure to be much simpler than expected. A new surface, the heliospheric polarity sheet was defined, which is a simple, single sheet across which the magnetic field polarity changes.

Since SEPs in gradual events are accelerated at shocks driven by fast CMEs, the solar wind flow and Alfvén speeds in a particular region of the corona/interplanetary medium are crucial for determining whether a given fast CME drives shocks or not. A comparison between fast CMEs and signatures of fast winds did not clearly show that shocks were more difficult to produce in the fast winds where the flow and Alfvén speeds are higher than in the slow wind. However, it was found that CMEs narrower than about 60 degrees were not associated with SEP events,

suggesting that there is a width threshold that fast CMEs must meet before they can produce shocks and SEPs.

3.8 FY 2003

We derived two new long-term geomagnetic indices: the inter-hour variability (*IHV*) and the inter-diurnal variability (*IDV*). Construction of the *IHV* revealed a significant calibration error in the geomagnetic *aa* index, the current gold standard of long-term indices. Studies based on the *aa* index (including one of our own) have indicated a doubling of the solar coronal magnetic field during the 20th century. An analysis based on the *IHV* and *IDV* indices indicates quite a different picture – that the background solar wind of the Sun (observed near solar minimum) has a relatively constant speed (~430 km/s) and field strength (6.4 nT) over the past century.

We related the time scale of solar eruptions to composition and charge state properties of solar energetic particle (SEP) events. Explosive events are linked to high-charge state SEP events while more gradual eruptions are associated with low Fe charge states.

The characteristics of solar source regions associated with the largest SEP events ($J(> 10 \text{ MeV}) > 100 \text{ pr/cm}^2/\text{s/sr/MeV}$) were investigated and we determined that such SEP Events preferentially originate from active regions on their first or second rotation.

We have determined the cause of the semi-annual variation of geomagnetic activity in 1954 and 1996, two years with pronounced six-month waves in geomagnetic activity. For both of these years, the semi-annual variation apparently resulted from equal contributions of the three principal mechanisms: axial, equinoctial, and Russell-McPherron. This is in contrast to the long run (decades to centuries) of geomagnetic activity where the six-month wave is primarily (~70%) due to the equinoctial effect. During 1954 and 1996, the axial and Russell-McPherron effects were enhanced by a favorable Rosenberg-Coleman polarity effect and a solar minimum solar magnetic field structure (low tilt angle).

Studies of the solar proton events as identified by impulsive increases in nitrates measured in a polar ice core from Summit, Greenland show a good relationship between great Geomagnetic Storms (as identified by a Greenwich Observatory publication) for the period 1840-1950. We found a distinct seasonal effect in the distribution of these impulsive nitrate events with substantially more large events detected in the second half of the Arctic year. We have no explanation for this effect. We also find a correspondence with the ~160 geomagnetic storm records with an apparent correspondence between the occurrence pattern of the smaller impulsive nitrate events (omnidirectional solar proton fluences between 0.5 and $1.0 \times 10^9 \text{ cm}^{-2}$) and the geomagnetic storm equinoctial frequency of occurrence pattern.

World grids of vertical cutoff rigidity values have been calculated for Epochs 1600, 1700, 1800, 1900, and 2000. Geomagnetic field models from the British Geological Survey were used for Epochs prior to 1900. The results show that there has been a major shift in the cutoff rigidity contours over the 400-year period coincident with the shifting of the location of the north geomagnetic pole. In addition, the world wide vertical cutoff rigidity values have steadily decreased over the 400-year period although not in a uniform manner.

We have prepared a dynamic geomagnetic vertical cutoff rigidity interpolation model that will be included in the next version of AFRL GEOSPACE. This software program, which currently has

the name of RCINTUT6, is intended to be a “stand alone” module that will run quickly and efficiently on a personal computer or work station generating vertical cutoff rigidity values for specified input coordinates. It will operate at any altitude, from in the earth’s atmosphere to beyond geosynchronous orbit.

With the group at the Nuclear Physics Institute of Moscow University, we determined the statistical distribution of decay times of solar energetic particle events over 28 years. Most decay phases were characterized by exponential decays in agreement with theoretical models. In most events the decay times decrease with increasing particle energies but are independent of the parent solar longitudes. The decay times range from about 10 to 30 hours. Extended periods of up to a month or more were found during which the decay times of all SEP events were similar.

Work with SEP events occurring in solar fast wind regions was continued. Additional SEP events from the years 2001-2002 were added to the statistics to confirm that SEP events occur frequently in fast wind regions even though the higher solar wind flow speeds and Alfvén speeds should limit CME-driven shocks and the lack of suprathermal ion velocity tails should limit the availability of seed particles for acceleration to high energies.

We Investigated the interaction between F-coronal dust grains and coronal mass ejections. The ion-drag force between CMEs and dust grains produces a solar cycle variation in the drift times of dust grains, producing lower densities and optical brightness at solar maximum. The dust grains have a negligible effect on CME propagation, but the CME magnetic field can make a significant displacement of the dust grains in its path.

We have found that anisotropies of solar wind heat-flux electrons are correlated with values of the solar wind plasma beta parameter. This helps to explain variations in the solar wind heat flux values that had earlier been attributed to magnetic disconnection of field lines from the solar corona.

WE also began work to compare calculated solar injection times of near-relativistic electrons with metric radio signatures from the Tresselt Observatory. No consistent signature has been found thus far for the apparent 10 to 30 minute delayed injections of the electrons. Some indications have been found that the delays are due to scattering of the first arriving electrons at 1 AU, but whether the delays are due to scattering or to later solar injections remains undetermined.

Work to compare the rise times of SEP events with the speeds of associated CMEs was begun to determine whether the speeds of CMEs are a determinant in the SEP profiles. For magnetically well connected SEP events a correlation was found, but no correlation was found for SEP events associated with eastern hemisphere or far western solar flare associations.

3.9 FY 2004

We have presented a case that waves in the solar atmosphere (including H α Moreton waves, Extreme-ultraviolet Imaging Telescope (EIT) waves, and radio type II shocks) are piston-driven by coronal mass ejections. The point of departure was a study by Zhang et al. (2001, ApJ) showing that the rapid acceleration phase of CMEs corresponded to the abrupt rise of the soft X-ray curve of the associated flare (i.e., the flare impulsive phase). Earlier studies had indicated that the CME launch characteristically preceded the flare and that the onset of metric type II emission was closely tied to the flare. Zhang’s result removes the timing problem for the CME-driven radio shock scenario.

Various aspects (ionizing radiation, solar energetic particles, CME speed, geomagnetic storm intensity, low-latitude auroral extent) of the solar-terrestrial event of 1859 were analyzed as an example of extreme space weather activity and they were placed in the context of other large events of the past 150 years, thereby establishing the current limiting ranges of these space weather effects.

We used Stanford magnetic field measurements to predict that the next solar cycle (cycle 24 with maximum ~2010) will be the smallest in 100 years. Previous predictions have used proxies (e.g., geomagnetic indices) for the solar fields with mixed results. For example, cycle 23 (maximum ~2000) was significantly over-predicted (SSN = 160 vs. SSN 120 actually observed). The key to the new technique is the use of direct solar observations and the recognition of the phase of the cycle at which the solar polar fields maximize – approximately three years before solar minimum.

Using the identification of large fluence solar proton events from polar ice combined with the frequency of large solar proton events in the modern era (1950-2003), we have found that there is a likelihood of an increased number of large fluence solar proton events during times when the interplanetary magnetic field strength is relatively low in the recovery period from the Maunder, Dalton and Gleissberg minima.

We have prioritized the large fluence solar proton events from polar ice and find 19 events in the period 1561-1950 that have a >30 MeV fluence larger than or equal to the fluence measured during the August 1972 episode of solar activity. From the use of historical records of geomagnetic disturbances, sunspot sightings and mid and low latitude aurora, we have found that the majority of these events are from solar activity near the central meridian of the sun and may be also associated with sequences of solar activity as the regions traverse the solar disk. The activity in August/September 1859, known as the Carrington region and flare of 1 September 1859, produced approximately 4-5 times the >30 MeV fluence of the August 1972 events as measured at Earth. The 4 largest solar proton events of the 23rd solar cycle do not exceed the >30 MeV fluence of the August 1972 event.

A study of radiation dose measured on a commercial aircraft flying from Los Angeles to New York City during the October 2003 Forbush decrease when compared with the expected dose during “quiet geomagnetic conditions” revealed that the present FAA CARI program used to calculate radiation dosage for flight crews does not adequately describe the radiation exposure from cosmic radiation during disturbed conditions, at least for that particular route.

Geomagnetic cutoff rigidity calculations using the newly released 9th generation IGRF model appropriate for Epoch 2000 have been started. Preliminary results show that there are still major increases in vertical cutoff rigidity over the North Atlantic Ocean area with major decreases in the rest of the Atlantic Ocean area.

We reviewed the observational properties of CMEs for the Chapman Conference on Solar Plasmas and Energetic Particles. Besides presenting the statistics of CMEs derived from 1996-2003 LASCO observations, several observational questions ripe for future investigations were selected. These were the nature of narrow CMEs; the role of coronal holes in CME occurrence and trajectories; and magnetic reconnection in CMEs. The nature of halo CMEs was explored and the possibility of using polarized and H alpha observations to determine the 3-D and cool component structures, respectively, was discussed.

Work on the statistics of solar wind heat-flux electron pitch angles was finished. The plots of the parallel-to-perpendicular electron ratios to the anti-parallel-to-perpendicular ratios show two

population peaks corresponding to heat-fluxes directed parallel and anti-parallel to the interplanetary magnetic field. They do not show a distinct population that might be expected to represent the bidirectional flows associated with close magnetic field topologies. The result calls into question the common technique of determining the magnetic field topologies based on the empirically determined bidirectional flows.

We investigated the relationship between impulsive near-relativistic electron events observed with the 3DP instrument on the Wind spacecraft and the solar signatures of shocks. Comparisons of the electron events with metric type II bursts observed at the Potsdam Observatory, decametric type II bursts observed on the Wind spacecraft, and CMEs observed on the SOHO LASCO instrument showed that most electron events are not associated with solar type II bursts and most solar type II bursts are not associated with electron events. However, shock acceleration can still be responsible for some electron events.

Timescales of 20-MeV SEP events were compared with the speeds, accelerations, and widths of associated CMEs to characterize the SEP timescales (onset times, rise times, and durations) as functions of solar source longitudes and to determine whether the CME parameters are a determinant in the SEP profiles. For magnetically well connected SEP events a correlation was found between the CME speeds and the SEP rise times and durations, but no similar correlation was found for SEP events associated with eastern hemisphere or far western solar flare associations. No correlations of SEP timescales were found with CME accelerations or with the O7/O6 solar wind ratios.

Work with Dr. Giuliana de Toma (HAO/NCAR) and scientific programmer Leslie Mayer (NOAA/SEC) was continued to significantly improve and generalize a synoptic map assembly routine originally written by Arge for a project to make specialized daily updated Wilcox Solar Observatory photospheric field synoptic maps. The original assembly code has been modified so that it can now construct maps of various types (daily updated, standard Carrington, any 360° longitude of rotation, and soon Zhao frame maps) using virtually any type of full disk solar data (e.g., magnetic field, He 1083nm, H α , etc.). Anything specific about the type or source of the data has been stripped from the main program, and its primary function now is simply to assemble the data (once in heliographic coordinates) into maps using a user defined weighting function. To put the data into a standardized format that the generalized assembly routine understands, small interface routines are now required for each new data source and type. This was necessary, as the file formats (e.g., fits, ASCII), header information, corrections applied (or not) are typically very different for data from each of the observatories and often even for different types of data from the same observatory. A remapping routine that converts solar disk observations into heliographic coordinates has also been written. This was done, as some observatories do not provide their data in a remapped format. Because of the 7.25° inclination of the Sun's rotation axis to the ecliptic, the Sun's polar fields are often not visible from the Earth (or a spacecraft at L1) for extended periods of times. As a result, data near the poles are frequently missing in the assembled synoptic maps. Filling the poles is a complicated process, and we have focused heavily on this issue to determine the best way to do this. We have incorporated a routine developed by Arge that can fill the poles using the observations lying near the boundary where the polar data are missing. Mayer has written and automated a routine at NOAA/SEC that retrieves remapped magnetograms from Mount Wilson Solar observatory, applies a variety of corrections, assembles them into daily updated synoptic maps, fills values missing at the poles, and then writes the maps into a file (FITS) using a standardized format. Our assembly routine has also been recently used to construct specialized EIT 195 nm and 284 nm synoptic maps that reveal the transient coronal holes that occurred during the May 12, 1997 halo CME. The maps were used in a study to understand the sources of the ambient solar wind stream structure around the time of this event. de Toma is developing a method to identify coronal holes using multiple types of data (e.g., EUV, He

1083.0nm, H α , and magnetic field) and the maps assembled with our generalized routine are being used in this effort.

3.10 FY 2005

We have developed a new long-term geomagnetic index (Inter Daily Variability (IDV)) that has the useful property of being highly correlated with the solar wind magnetic field strength and essentially independent of solar wind speed. This index was used to deduce IMF strength from 1872-present.

Two unusual solar ground level events associated with weak solar flares were analyzed and were attributed to shock acceleration of an enhanced seed population ($> 10^3$ above background at 10 MeV at 1 AU). This bears on the current key question in solar energetic particles studies: the origins of the highest energy particles.

The Homogeneous Coronal Data Set (HCDS) based on worldwide observations of the coronal green line since 1939 have been revised to remove an anomaly in the HCDS-derived Coronal Index (CI) for years before 1965. Revised HCDS made available on the world-wide web.

A new type of large-scale propagating chromospheric disturbance has been identified in ISOON data. In the eruption examined, the disturbance consisted of four nearly cospatial propagating chromospheric brightenings. The speeds of the propagating disturbances causing the brightenings were 600-800 km s⁻¹. The inferred propagating disturbances had some of the characteristics of H α and EIT flare waves (e.g., speed, apparent emanation from the flare site, subsequent filament activation). However, they differed from typical H α chromospheric flare waves (also known as Moreton waves) because of their absence in off-band H α images, their small angular arc of propagation ($< 30^\circ$), and their multiplicity. Three of the four propagating disturbances consisted of a series of sequential chromospheric brightenings of network points that suddenly brightened in the area beneath a transequatorial loop that disappeared earlier. SOHO MDI magnetograms showed that the successively brightened points that define the inferred propagating disturbances were exclusively of one polarity, corresponding to the dominant polarity of the affected region. It appears that the sequential chromospheric brightenings represent footpoints of field lines that extend into the corona, where they are energized in sequence by magnetic reconnection as coronal fields tear away from the chromosphere during the eruption of the transequatorial CME.

We have identified the 19 solar proton fluence events from polar ice in the period 1561-1950 that have a > 30 MeV fluence larger than or equal to the fluence measured during the August 1972 episode of solar activity. The activity in August/September 1859, known as the Carrington region and flare of 1 September 1859, produced approximately 4-5 times the > 30 MeV fluence of the August 1972 events as measured at Earth. In a study of the solar proton events in the past five solar cycles it was found that the present 23rd solar cycle has the largest number of discrete solar proton events and also the largest fluence over the solar cycle. The fluence is slightly larger than that inferred for the 19th solar cycle for protons > 10 MeV.

Two distinct sets of extremely large > 30 MeV solar proton fluence events were identified. One set represents solar proton events associated with solar activity on the western hemisphere of the sun. These events are called “near sun injection events” as the particles traverse the interplanetary medium between the sun and the earth along the interplanetary magnetic field lines that connect the earth with the sun at the time of the event. The second set represents the solar proton events associated with solar activity near the central meridian of the sun. These events are

called “interplanetary shock-dominated events” as the fast traveling interplanetary shock continues to accelerate particles while traversing the sun-earth distance. The separation of the events into these two groups was used to estimate the solar proton time-intensity profile that might have been present from the Carrington 1859 flare.

Simple concentric geomagnetic latitudes were found to be a better estimate for the mid and low latitude extent of geomagnetic disturbances than geomagnetic cutoff rigidities. However, geomagnetic cutoff rigidities are a better indicator of the latitudinal extent of solar proton fluxes during a major high energy solar proton event.

The vertical geomagnetic cutoff rigidity values for a World Grid 1 degree in latitude and 5 degrees in longitude were calculated for Epoch 2000. This represents a more accurate set of vertical cutoff rigidity calculations at 20 km than previously available, primarily because of the improved geomagnetic field models and the increased precision of the geographic grid spacing. This grid will be used by the FAA to determine radiation dose to aircrew members during commercial airline flights.

Work on the review of the observational properties of CMEs for the Chapman Conference on Solar Plasmas and Energetic Particles was completed and published in an AGU Monograph. Besides presenting the statistics of CMEs derived from 1996-2003 LASCO observations, several observational questions ripe for future investigations were selected. These were the nature of narrow CMEs; the role of coronal holes in CME occurrence and trajectories; and magnetic reconnection in CMEs.

The comparison of CME properties associated with 20-MeV proton-rich and proton-poor events was carried out. Two sets of proton-rich and proton-poor fast CMEs were selected for comparison. The main difference was the brightness of the CMEs; those associated with SEP-rich events are very bright, indicating high CME masses while the much fainter CMEs are associated with SEP-poor events. The preferred interpretation is that fast CMEs must be wide in angle to produce shocks that accelerate energetic particles.

The solar injection times of near-relativistic electrons as determined from the time versus $1/\text{velocity}$ plots was examined in detail, with visitor B. Ragot, to determine the reliability of the $1/\text{velocity}$ technique. The technique assumes that first arriving electrons are scatter-free and electrons of all energies travel the same interplanetary path to reach 1 AU. The $1/\text{velocity}$ plots are presumed to give straight-line fits, but using data from the 3DP electron detector on the Wind spacecraft the derived travel distances were generally unphysically small, which calls into question the validity of the basic technique.

The association of Forbush Decreases (FDs) with CMEs observed with the SMEI instrument was investigated. Preliminary results indicate that the CMEs associated with large and impulsive FDs of at least 2% in counting rates are readily observed in the SMEI.

Work was done with Center for Integrated Space Weather Modeling (CISM) team members to develop a set of metrics for validating solar coronal models (such as the potential field source surface (PFSS) model used in the Wang-Sheeley-Argé (WSA) model and SAIC's 3D MAS coronal model. Initial results indicated that the coronal holes predicted by the MAS model were generally too small when compared to both observations and those predicted by the PFSS model. It was subsequently discovered that the MAS code needed to be run for a longer period of time for the numerical solution to reach a true equilibrium. Such validation work is extremely useful to

modelers, for it helps them identify problems with their codes, constrain free parameters, and in this particular case, determine appropriate model run times.

Participation continued in a joint AFRL-CISM effort to couple the coronal portion of the WSA solar wind model with the Odstrcil 3D MHD ENLIL solar wind code. The coupled code provides global 3D MHD plasma parameters out beyond 1AU, as opposed to 2D solar wind speed and IMF polarity in the ecliptic, which is the output of the WSA model. Work continued on improving the photospheric field synoptic maps used to drive the coupled model. For example, a routine was developed that interpolates between the updated maps (they are not updated at uniform time intervals) in time, so that the model can read in maps in uniform time steps.

A synoptic assembly code has been used to construct improved photospheric field maps from both Mount Wilson (MWO) and Wilcox (WSO) solar observatories using their remapped magnetograms. Our method applies corrections to the magnetograms not usually made by these two observatories except for effects due to differential rotation, which MWO takes into account in their maps. A set of new WSO synoptic maps was run through the WSA model and the results are extremely encouraging

3.11 FY 2006

A large geomagnetic storm associated with a disappearing high-latitude solar filament was identified. Such events underscore the importance of coronal mass ejections vs. solar flares for space weather.

Electron-to-proton ratios were examined for SEP events observed during solar cycle 24. The analysis revealed two distinct classes of SEPs: (1) a group of events with peak proton intensities $< 3 \text{ pr cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ that have electron to proton (e/p) ratios ranging from $\sim 10^2 - 2 \times 10^4$, and (2) a well-defined branch that spans peak proton intensities from $\sim 3 - 10^4 \text{ pr cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ with e/p ratios ranging from $\sim 10^1 - 2 \times 10^2$. Events with strong abundance enhancements of trans-Fe elements form a prominent subset of “population 1” and are absent from “population 2”. For a sample of poorly-connected SEP events, population 1 largely disappears, and population 2 is observed to extend down to low ($< 10^{-1} \text{ pr cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) proton intensities. Plots of 0.5 MeV peak electron intensity vs. $> 30 \text{ MeV}$ peak proton intensity yield comparable results. The SEP events in population 2 are highly ($\sim 90\%$) associated with decametric/ hectometric (DH) type II bursts vs. only a $\sim 20\%$ association rate for population 1 events. Population 2 events have flatter electron (0.5 - 4.4 MeV) and proton spectra (10 - 30 MeV) than those in population 1. Based on their high e/p ratios, trans-Fe enhancements, poor association with DH type IIs, and inferred small “emission cones”, population 1 events are attributed to acceleration in solar flares. For population 2 events, evidence for a dominant shock process includes their flatter spectra, apparent wide-spread sources, and high association with DH type II bursts.

Work with the FAA has examined the computed radiation dose at commercial aircraft altitudes during solar cosmic ray events. The preliminary result of this study is that there have been no events during the last two solar cycles where the hourly average exposure at 40,000 feet would have exceeded 20 micro-sieverts per hour. We have specifically analyzed the anisotropy of the January 2005 solar cosmic ray event to determine the radiation distribution as a function of the solar cosmic ray proton anisotropy. We have also determined that the “urban legends” of high radiation doses during high-energy solar cosmic ray events are the results of simplistic calculations that do not represent today’s knowledge. The most common error is the application of straight-line power law spectra from very high energies to the biologically effective energies.

Involvement continues in the analysis of nitrate precipitation in Greenland ice cores with the objective of ultimately having a better calibration between the known solar cosmic ray events and the NOY deposition in the polar ice. A recently obtained shallow ice core covers the period from approximately 1940 to 2004. Improved analytical techniques have confirmed each of the previously identified nitrate deposition events found in the GISP-H ice core drilled in 1992. These improved continuous flow analytical techniques have an approximate factor of 5 improvement in the sensitivity and time resolution from the previous method. Evidence of enhanced nitrate deposition in the polar ice for every known solar cosmic ray ground-level event from 1940 through 2004 has been found.

The solar injections of near-relativistic (NR) electron events observed at 1 AU appear to be systematically delayed by ~ 10 minutes from the associated flare impulsive phases. We compared inferred injection times of 80 electron events observed by the 3DP electron detector on the Wind spacecraft with 40-800 MHz solar observations by the AIP radio telescope in Potsdam-Tremsdorf, Germany. Other than preceding type III bursts, we found no single radio signature characteristic of the inferred electron injection times. The injection delays did not correlate with the 1 AU solar wind beta or B, but did correlate with densities n and inversely with speeds V , consistent with propagation effects. Electron events with long (> 2 hr) beaming times at 1 AU are preferentially associated with type II bursts, which supports the possibility of a class of shock-accelerated NR electron events.

The Proton Prediction System (PPS) is a program developed at the Air Force Research Laboratory (AFRL) to predict solar energetic ($E > 5$ MeV) proton (SEP) intensities at 1 AU following solar flares. The input parameters are solar-flare peak or time-integrated X-ray or radio fluxes and their times of onsets and maxima, and solar flare locations. A limited validation of the PPS using 78 GOES solar X-ray flares of peak intensity $> M5$ with well associated Ha flare locations was done. Predicted peak proton intensities ($E > 10$ MeV) and event onset and rise times were compared with SEP events observed by GOES. All GOES $E > 10$ MeV SEP events above 10 proton flux units (pfu) during the same time period were selected to compare with those predicted by the PPS. With the M5 X-ray flare threshold, the PPS yields approximately equal numbers of correct predictions, false predictions, and missed 10-pfu SEP events.

The NASA Sentinels Team Definition report was finished in 2005 and issued as a NASA publication. It proposes a 4-spacecraft mission to the inner heliosphere (0.25 to 0.7 AU) to study solar energetic particles and solar wind fields and densities. Sentinels is a mission of the NASA Living with a Star program to be launched about 2014. The report outlines the science to be studied and provides suggested instrument payloads and mission orbits. The 4 inner heliospheric spacecraft are complemented by a near-Earth spacecraft to observe the solar corona and a far-side spacecraft to obtain magnetograms.

A detailed study of the sources of the solar wind around times of two similar and “simple” halo CME events: the April 7 and May 12, 1997 halo CMEs, was conducted. The Wang-Sheeley-Argue (WSA) model describes the observed (at L1) ambient solar wind stream structure around the time of the May 15 ICME generally well, except for the ejecta itself. (The model is not designed to detect ICMEs, so the fact that it misses them is not unexpected.) For the April 7 event, the model did less well. It missed both the ejecta (as observed at L1) on April 10 and the stream that followed behind it. We came up with a number of possible reasons why this stream was missed (e.g., imprecise polar fields in the photospheric field synoptic maps used to drive the model, the source of the stream was a transient coronal hole, etc.). A major difference between the two events is that the (most likely) source of the stream following the passage of the April 10 ICME is

a coronal hole extension located in the northern hemisphere that had an active region nearby, while the source of the stream following the May 15 ICME was a coronal hole in the south with no active region close by. This led us to investigate whether the model has problems in predicting the solar wind when its source is near an active region. We used two years of NSO/SOLIS photospheric field Carrington maps (CR2011-2032) as input to the model and found that it frequently fails at matching the observed solar wind speed when the source of the solar wind lies near an active region. However, it is usually quite good at predicting the IMF polarity of the solar wind and therefore (presumably) identifying its source regions back at the Sun. The ability of the WSA model to successfully predict solar wind speed thus appears to be a function of the proximity of its source region to strong active regions. That is, if the source region is close to (far from) a strong active region, then the model's speed predictions are generally poor (good).

We applied a polar field correction technique that we developed [Arge and Pizzo, 2000] to an 11 year set (1995-2005) of LOS photospheric magnetic field Carrington maps from Mount Wilson Solar Observatory (MWO). We then used both the corrected and uncorrected maps in the WSA model. The results were then compared with each other and with the observations from the WIND & ACE spacecraft. We found significant improvement in the model predictions when the polar fields are strong (e.g., during minimum) and when the source of the solar wind is from one of the polar coronal holes.

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A revision of the standard two-class picture of SEP events which expanded the description of the large gradual (shock) class to include shock geometry and seed particle population was developed.

Evidence was presented for a “floor” in the solar wind magnetic field strength. At 1 AU in the ecliptic plane, the “floor” is characterized by a field strength of ~ 4.5 nT (in solar rotation averages) to which it returns for a few rotations during every solar minimum. Indirect evidence from cosmogenic nuclei suggests that the IMF strength near Earth persists at this level during Grand Minima such as the Maunder Minimum. Outside of the ecliptic plane, the floor manifests itself as a constant radial open flux of ~ 3 nT, relatively independent of latitude and solar polar field strength. We equate the “floor” with a constant open magnetic flux of the Sun which is a basic ingredient of a recently proposed model of the solar magnetic field.

A new long-term geomagnetic index (Inter Hour Variability (IHV)) was developed and used in conjunction with the previously developed Inter Daily Variability (IDV) index to infer solar wind speed back to the late 19th century.

Using a solar proton database for the past five solar cycles (1954-2007) we have determined the total solar proton fluence above 10 MeV and the number of discrete events that occurred each cycle. We find: (1) The number of discrete events in cycles 19-22 were essentially the same; (2) Cycles 20 and 21, at the beginning of the space era, were relatively benign with respect to solar proton fluence; (3) Approximately 16% of the total number of discrete events each cycle are relativistic solar cosmic ray events (i.e. GLEs); (4) Cycle 23 has been the most active cycle since 1954. We also find that the number of GLEs can be associated with a relatively small number of solar active regions with each region producing several large events in a sequence of activity. Of the 70 GLEs between 1942 and 2006, 36 of these events were associated with only 15 active solar regions.

A direct comparison of impulsive nitrate enhancements observed in multiple polar ice cores from both hemispheres was presented for the years 1940-1950. During that time period, four ground-level solar cosmic ray events (GLEs) were recorded by ionization chambers. We showed that large and sudden enhancements in the nitrate records from both hemispheres were observed within weeks of the dates of the GLEs. The observation of impulsive nitrate enhancements simultaneously in both hemispheres shortly after a large solar proton event is strong evidence in support of a causal connection and argues strongly for rapid gravitational sedimentation of atmospheric nitrates.

A world grid of vertical cosmic ray cutoff rigidities was calculated using the Definitive International Geomagnetic Reference Field for Epoch 2000.0. These cutoff rigidity values were specifically computed for updating the aircraft radiation dose. These cutoff rigidity values show the effects of the continued evolution of the geomagnetic field. The average cutoff values continue to decrease especially in the South Atlantic and South American areas. However, in the North Atlantic and the east coast of the North American continent, the cutoff values are increasing.

Coronal holes (CHs) are the sources of fast wind flows and their boundaries are sources of the slow solar wind. The relationship between the changes occurring at those boundaries and the generation of the slow solar wind is a current topic of great research interest. It has been known since their discovery on Skylab that equatorial extensions of polar CHs appear to rotate quasi-rigidly despite the shearing effects of the differential solar rotation. The question then is to understand how the necessary magnetic reconnection must take place at the CH boundaries to maintain that form. It is widely modeled as interchange reconnection, in which open and closed field lines reconnect to form new sets of open and closed field lines. A study of soft X-ray images showed only smoothly varying boundaries with neither large-scale X-ray transients nor coronal bright points being significant factors in boundary changes. High spatial (0.5 arc sec pixels) and temporal (~ 5 minutes) resolution observations with the TRACE spacecraft provided a new opportunity to study the CH boundary changes through magnetic reconnection. We worked with personnel at Smithsonian Astrophysical Observatory to make movies from TRACE observations with the 195A (Fe XII) observations of a CH in December 2000. The CH boundary changes were observed on short (~ 5 min) and long (~ 10 hours) timescales but showed no correlation with photospheric magnetic field enhancements and no energetic jets marking episodes of magnetic reconnection. The CH boundary changes most likely occur in the high corona.

Considerable work has been done recently on observations of near-relativistic ($E > 40$ keV) electron events. Contrary to observations with earlier instruments, the times of solar injections have been found to be ~ 10 minutes after the preceding metric and decametric type III radio bursts occur. This delayed injection has led to several suggestions about the conditions under which the electrons are injected. A principal question is whether the high-energy electrons are produced in CME-driven shocks. We reviewed a combination of the recent literature and the extensive older published observations at relativistic and near-relativistic energies to produce an integrated view of electron acceleration and propagation. In general the relativistic electrons are mostly produced at shocks while the near-relativistic electrons originate more often in impulsive flare events.

The onsets, rise times, and durations of solar energetic particle (SEP) events observed at 1 AU vary considerably, even for events from comparable solar longitudes. We investigated whether the ambient solar wind (SW) streams play any role in those variations. The times from CME launch to event onset, rise times, and durations of 20 MeV solar proton events observed on the

Wind spacecraft during 1998-2002 were compared with their associated SW components classified as transient structures, high-speed streams, and slow wind. The SEP events were sorted into five groups of solar source longitudes to compensate for well known variations of timescales with connection longitudes. We found only a slight trend for the shortest timescales in transient structures, but otherwise no dependence of any time scales on SW stream type. In particular, there was no evidence for enhanced convective and adiabatic energy losses in low-speed streams or for enhanced scattering in high-speed streams.

We have worked with Guilian de Toma (HAO/UCAR) on a project to better understand the role that solar polar magnetic fields play in determining the shape of the heliospheric current sheet and the geometry of coronal holes near solar minimum. Our efforts so far have been focused primarily on the current and last solar cycles. The cycle just ended (cycle 23) was weaker magnetically compared to cycle 22 (and even compared to 21). The polar magnetic fields are presently about 40% weaker than during the previous minimum, and the associated polar coronal holes are smaller as well. Further, there are several low-latitude coronal holes which continue to be a significant source of the solar wind observed at the Earth. We have used potential field source surface (PFSS) model computations and observations from 1996 and 2006-2007 to identify the main sources of the solar wind during these two epochs and have artificially modified the polar magnetic fields for both periods in an effort to better understand the role they play in determining the morphology of the corona and heliospheric current sheet. We draw three main conclusions from our studies. First, based on the level of magnetic activity, the morphology of the solar corona, and the shape of the heliosphere, we believe (as of September 2007) that the Sun has not yet reached solar minimum. Second, changing the polar magnetic flux during this cycle so that it matches the values seen in 1996 appears to flatten the heliospheric current sheet and makes the polar coronal holes a more important source of the solar wind, but they still do not appear as dominant as in 1996. Low-latitude magnetic activity is thus still playing an important role in determining the global coronal field. Third, it is the balance between the level of magnetic activity at low latitudes and the strength of the polar magnetic fields that determines the morphology of the corona and heliospheric current sheet.

A good deal of effort last year was focused on improving the method used to correct the polar field measurements found in solar synoptic maps. In general, line-of-sight (LOS) photospheric field measurements near the Sun's poles are often highly unreliable because of their close proximity to the limb and because the Sun's rotation axis is inclined 7.25° to the ecliptic plane. The least reliable measurements in photospheric field synoptic maps thus tend to be those located near the poles. Since coronal and solar wind models (both simple and advanced) are very sensitive to the Sun's polar fields, it is especially important that they are known as well as possible. In an effort to compensate for these problems, we have worked to improve upon our original polar field correction technique developed in 2000 [Arge and Pizzo, 2000]. The approach that appears to work best (so far) for correcting the poles during intervals when they are poorly observed is (1) use the observations when the poles are well observed (i.e., when they are directed nearly at maximum toward the Earth) but only those values immediately before and after the problematic period, 2) fit a low order (e.g., second) polynomial curve to these values, and 3) use the resulting polynomial to adjust the values of the polar field in the synoptic maps. This approach was applied to a large set of LOS photospheric magnetic field Carrington maps from Mount Wilson Solar Observatory spanning nearly an entire solar cycle (1995-2005). These maps along with ones with no polar corrections were then used as input to the WSA model and the resulting solar wind speed predictions at L1 compared. For the period 1995-1998 (i.e., near last solar minimum), we found a 15 to 20% improvement in model skill for the maps with the polar field corrections applied relative to those with no corrections applied. We conclude that

correcting the polar fields is most important during solar minimum when the fields are strong there and thus have greatest influence on the global magnetic field configuration.

We worked with Boston University graduate student, Sarah McGregor, on a project to improve the coupling between the inner and outer coronal field models within the Wang-Sheeley-Argge (WSA) model. WSA makes use of coupled Potential Field Source Surface (PFSS) and Schatten Current Sheet (SCS) models to reconstruct the coronal magnetic field on the basis of the observed line-of sight photospheric magnetic field, and a 1D kinematic code to propagate the solar wind to 1 AU. The source surface serves as the outer boundary of the PFSS model and the inner boundary of the SCS model. Known discontinuities arise in the tangential components of the magnetic field across this surface owing to differences in the imposed boundary conditions. We introduced a more flexible coupling between the two models in an effort to reduce the discontinuous behavior of the magnetic field across the model interface surface. The approach used is to set the source surface radius to a value larger than normal (i.e., $2.5 R_s$) and then introduce a new, second heliocentric surface with a radius smaller than that of the source surface. The radial magnetic field values on this new surface are then used as input to the SCS model. This approach helps avoid using the magnetic field values near the source surface where the fields are required to be radial, which is generally known to be a poor assumption. This simple modification substantially reduces the kinks in the field lines observed in the original model at the point where the two solutions are matched, and hence substantially reduces the currents flowing on this boundary surface.

Two coronal mass ejections (CMEs) were tracked through the LASCO field of view (FOV) within 30 Ro and later as interplanetary CMEs (ICMEs) through the SMEI FOV from 80–150 Ro. They were also associated with erupting filaments that were observed by EIT, providing information on the trajectory of propagation. This allowed three-dimensional reconstructions of CME/ICME geometry, along with corrected (not sky plane projected) measurements of the distance-time (d-t) plots for each event. An investigation of morphology suggests that the fine structure of the CMEs are eroded by the solar wind, and curvature becomes more sharply convex outward, suggesting that the ICME footprints remain fixed to the Sun even at 0.5 AU. The observations were compared with two models describing the evolution of the CME/ICMEs at large distances from the Sun (far from the launch mechanism and the effects of gravity and solar pressure) and considering two drag models: an aerodynamic drag and a snow-plow model. There was little difference between them, and their d-t profiles matched well with the SMEI data for Event 1. Event 2 showed a net acceleration between the LASCO and SMEI fields of view and we found that we can match the data for this event well by introducing a driving Lorentz force. ICME mass almost doubled as a result of swept up solar wind material from the snow-plow model.

4. CONCLUSIONS

The research discussed herein spans a large range of solar-terrestrial phenomena. The final section showing the task publications makes clear that a considerable amount of valuable work has been performed. An abbreviated listing of some more recent research topics is the following: 1) modifications to models of solar wind flow based on solar magnetic field measurements; 2) CME propagation in the interplanetary medium based on LASCO and SMEI observations; 3) SEP event time scales as functions of solar wind types; 4) magnetic reconnection at the boundaries of coronal holes, which form the interface between high and slow speed streams; 5) use of polar ice core measurements of nitrate enhancements to determine large SEP fluences back to 1610; 6) development of new geomagnetic indices to deduce the history of the solar wind and

interplanetary magnetic field at 1 AU; 7) sensitivity of solar wind model predictions to flows from near or in solar active regions; 8) requirements for a fleet of near-Sun satellites to measure fields and particles; 9) validation of the AFRL Proton Prediction System to predict occurrences of SEP events and their peak intensities; 10) properties of solar $E > 30$ keV electron events and their delayed arrivals at 1 AU; 11) use of e/p ratios to determine the sources and populations of SEP events; 12) the validity of the $1/V$ plots used to determine solar injections of energetic particles; 13) large Forbush decreases and associated SMEI CMEs; 14) new geomagnetic index to correlate with interplanetary magnetic fields; 15) waves in Ha images showing brightenings at loop footpoints; 16) brightness differences between fast CMEs with and without associated SEP events; 17) optimization of solar magnetic field maps for various inputs and missing polar data; 18) characterization of SEP event time scales and correlations with CME parameters; 19) statistics of solar wind heat-flux electron pitch angles; 20) type II radio bursts as sources of energetic electron events observed at 1 AU; 21) solar polar fields as the basis for prediction of the subsequent cycle sunspot number; 22) determination of the source of shocks producing radio type II bursts; 23) statistics of the solar wind heat-flux anisotropies; 24) the September 1859 solar event as a case of extreme solar activity; 25) the interaction between the F corona dust and CMEs; 26) the occurrence of SEP events in fast solar wind regions; and 27) the decay times of SEP events.

APPENDIX

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